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GASEOUS RADIATION IN HYPERSONIC
STAGNATION POINT FLOW

ARF Project A6011, Semi-Annual Report
ARPA Order No. 322-62, Amendment 1
Contract No. Nonr-3884(00)

ARMOUR RESEARCH FOUNDATION
of
ILLINOIS INSTITUTE OF TECHNOLOGY
Technology Center
Chicago 16, Illinois

GASEOUS RADIATION IN HYPERSONIC STAGNATION POINT FLOW

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for

Advanced Research Projects Agency
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FOREWORD

This is the first semi-annual report for Contract No. Nonr 3884 (00), covering the period June 15, 1962 to December 15, 1962. The program is being carried out under ARPA Order No. 322-62 and Amendment 1, and is being technically monitored by Mr. Morton Cooper, Office of Naval Research. Personnel who have contributed to the work during the report period include D. S. Hacker, Imants Reba, L. N. Wilson, and E. Wolthausen.

Respectfully submitted,
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GASEOUS RADIATION IN HYPERSONIC STAGNATION POINT FLOW

I. INTRODUCTION

Measurement of gaseous radiation to which vehicles are exposed during hypersonic flight presents many problems. On the other hand, radiation measurements in the laboratory also present difficulties, since true flight conditions are difficult to simulate. In the past, attempts have been made to predict the equilibrium or non-equilibrium radiation using the results obtained from measurements of emission behind the normal or reflected shock waves produced in shock tubes. Application of results thus obtained to predictions of radiant heating under in-flight conditions has been inexact for two reasons. Firstly, the predictions have necessarily been based on approximate descriptions of conditions within the shock layer. Secondly, the radiation measurements made across the shock tube may not truly represent the radiation incident upon the model, since radiation impurities in the wall boundary layer may contribute.

In view of these considerations, a departure in approach has been made in the current ARF program of radiation measurements. Intensity measurements are being made at the stagnation region of a hemisphere-cylinder. Experimental results obtained thus far indicate that impurity radiation of the type encountered along the shock tube wall is not detected. In addition, stand-off distance measurements are being performed to gather more knowledge about the flow field characteristics and the radiating volume as encountered around bodies in shock tube flows.

The aim of the program is first to determine the contribution of radiation to heat transfer rates measured in shock tube flows. At high stagnation enthalpies, heating rates have been measured which exceed those predicted by boundary-layer conduction theories. There is some speculation that this may be the result of radiative transfer to the model surface. Direct measurements of total radiation at the stagnation point of the model will determine if radiation is indeed contributing significantly.

A second aim of the program is to use the results of such measurements to predict the radiative heating of actual re-entry bodies. This can be done for equilibrium flow, when the actual temperatures and densities are duplicated in the shock tube, and the body geometry and size are the prime considerations in scaling the model results. Thus, reasonable predictions of radiation to the actual vehicle can be made. On the other hand, where the shock tube flow is not in equilibrium at the stagnation point, scaling of the results is difficult if not impossible. Hence, one must also determine the limits of the shock tube test parameters (pressure, temperature, Mach number) which define flow regimes where data can be applied directly to problems of re-entry.

II. EXPERIMENTAL FACILITY AND TECHNIQUES

Experimental studies discussed here have been made in a 3-inch buffered shock tube using 3/8-inch and 3/4-inch diameter hemispheric cylinders. The shock tube is shown in Figure 1. Experience has shown that a buffered shock tube with argon as a buffer gas can be used advantageously to generate high shock Mach numbers[1]. However, in radiation studies, an argon buffer tends to produce considerable inconsistencies in light intensity levels. This is caused by the very diffuse argon-air contact interface. To eliminate all possible causes which contribute to the scatter of data, the present phase of the investigation uses dry air buffer as a

Figure 1 ARF 3 INCH BUFFER SHOCK TUBE FACILITY

substitute for argon with a pressure ratio of unity across the buffer diaphragm. Particular care is exercised in test run preparation. Wall contamination in the tube is kept at a minimum by the use of a nickel-chrome plated interior surface and the tube is outgassed to 5 microns pressure before each experiment. Driver contamination is reduced after each run by thorough cleansing of the tube with a sequence of ethanol rinses. Further minimization of sources of contamination is attained by the use of scribed aluminum buffer diaphragms rather than Mylar films.

The shock Mach number is monitored at two photomultiplier stations which are located 28 inches apart immediately upstream of the test section. The shock passage is viewed through collimating slits 0.003 inch wide and 1/2 inch long. Thus, signals with high rise time characteristics can be obtained. Photomultiplier signals are used to trigger and stop a Beckman counter. Simultaneously, signals are recorded on a Tektronix 555 oscilloscope. This method furnishes a permanent record of shock velocity and enables one to correct any counter errors which are due to variations in trigger and stopping sensitivity and signal rise time characteristics.

A. Stagnation Point Radiation Measurements

If the flow behind the model bow shock is in equilibrium, the intensity of the radiation to the stagnation point should vary almost directly with the shock standoff distance or approximately as the model scale. However, as the relaxation distance becomes appreciable at the lower densities, but still less than the shock standoff distance, the non-equilibrium chemical processes will become important, and the radiant intensity should not vary appreciably with scale. As the density is decreased still further, so that the relaxation distance becomes greater than the shock standoff distance, the integrated radiation again becomes scale dependent. Hence, by comparing the radiation measurements using two models of different size in identical flow fields, it should be possible to determine where non-equilibrium effects become significant.

To accomplish this, total radiation intensity is measured at the stagnation point of two hemispherical cylinders, 3/8 inch and 3/4 inch in diameter. Through a passage in each model, a 0.120-inch diameter quartz rod, supported by two O-rings, is extended to the stagnation point at the hemispherical end. The quartz rod is used to collect the total radiation incident on the stagnation region. This is piped through an L-shaped light tube to a photomultiplier.

Although this scheme is quite simple and measurements made through the model show complete absence of an impurity spike at shock arrival, a number of difficulties have been encountered in rendering the test results reproducible. As mentioned, care was taken in test preparation procedures to minimize the level of tube contaminants. In spite of these precautions, two-fold variations in the light output were observed, and these could not be explained as impurity radiation. Peculiar electrical outputs were observed during monitoring of radiation at various shock tube sections during the test runs. A sequence of test runs disclosed that the light output was being modulated by a non-uniform potential distribution on the shock tube walls, particularly the tube end plate. Such non-uniformities are easily generated if, for example, the shock tube is not properly grounded. Single-point grounding and provision for maintaining good electrical contact at all O-ring seals between sections of the shock tube have resulted in a uniform shock tube potential. This has greatly improved reproducibility of of light intensity measurements made along the shock tube wall.

Studies have been resumed using the stagnation point light tube. It now appears that data scatter will be sufficiently small to permit useful interpretation. Preliminary data using two model sizes have been obtained at a stagnation temperature of about 6300°K, with initial pressures between 1.5 mm and 0.5 mm. The light output is essentially constant throughout flow duration and the intensity ratio varies almost directly with the model size. More data are needed in order to fully evaluate their significance. In addition, these measurements have yielded information about the flow duration which is essential for the photographic measurement of standoff distance.

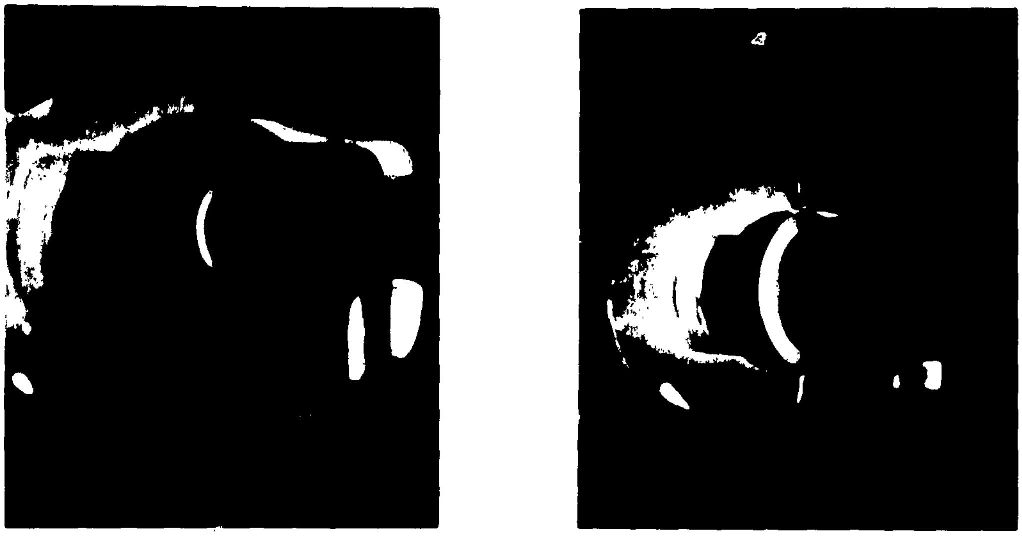
B. Standoff Distance Measurements

Recent examinations of the flow field have shown that pre-dissociation in the free stream can considerably change the standoff distance as well as the bow shock curvature[2]. At the present time, few experimental data have been collected for such measurements at low density; none at least in shock tube flows. Standoff distance measurements in shock tube flows would provide an experimental verification for various existing theories. Likewise, departures from experimental results would indicate that the inherent assumptions in these theories are not valid in the flow regime in question. Such knowledge used separately or in conjunction with the total light intensity measurements may constitute an effective means for the evaluation of the pre-dissociation effects and may indicate flow regimes where non-equilibrium is pronounced. Consequently, attempts were made to develop a photographic technique which could be applicable to very low density flow regimes.

Conventional flow visualization techniques such as interferometry, schlieren, and shadowgraph failed to produce the desired results. However, satisfactory results were obtained using direct photography. Typical pictures are shown in Figure 2. Light intensity measurements have disclosed that a luminous front at the stagnation point of the model exists only once during the entire shock tube run duration. The luminosity is essentially constant and lasts between 20 μ sec and 100 μ sec, depending on shock Mach number and density. On the other hand, side wall photomultipliers disclosed that the reflected wave makes several passages in the duration of the shock tube run. To avoid overexposure from these reflected waves after the luminous region at the stagnation point of the model has ceased to exist, a relatively fast shutter was required.

A shutter which can close within 30 μ sec was constructed. It is shown in Figure 3. The aperture diameter of the shutter is 0.140 inch. The closing is accomplished by a plunger driven by an exploding wire. Best results were obtained with 0.005-inch diameter bronze wire 0.200 inch long. Power was obtained from 0.6 μ F capacitor bank charged to 12,000 volts. The shutter is triggered from a photomultiplier which senses shock passage. By adjusting the time delay, the development of the luminous region at the stagnation point of the model can be studied.

A sequence of photographs has been obtained with closing times of 20, 30, 40, 60, and 80 μ sec after the initiation of the flow around the model, determined previously in the light tube tests. In this sequence, no changes in the standoff distance have been detected. This means that the flow establishment time is less than 20 μ sec and light tube measurements are made during an essentially steady state flow. Exposures longer than the



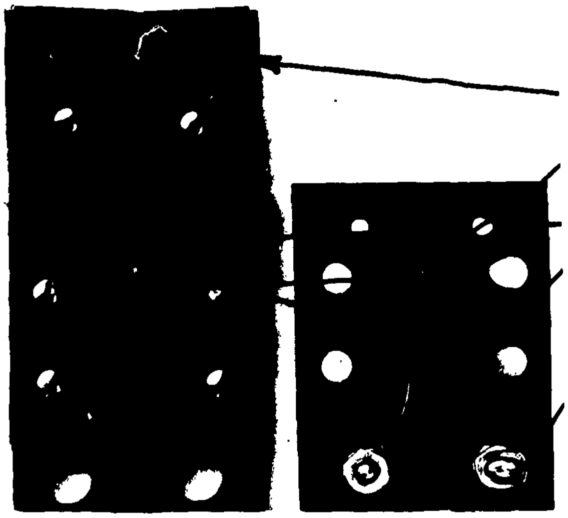
a   b

Figure 2 FORMATION OF BOW SHOCK AT $M_s = 12$

$p_1 = 0.5$ mm Hg, Exposure $\sim 170\ \mu$ Sec.

a. Model 3/8 inch Dia.

b. Model 3/4 inch Dia.



Housing (Bakelite)

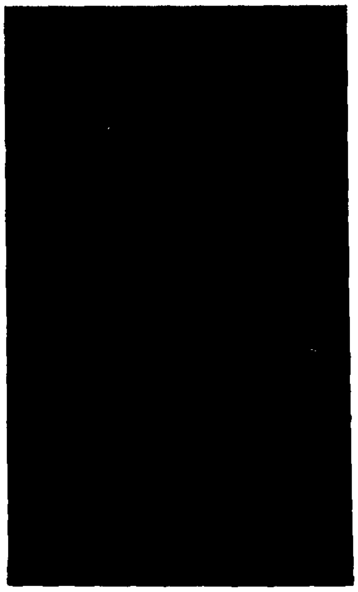
Aperture

Shutter

Exploding Wire

Electrical Connections

Shutter Assembly



Shutter (Black Paper)

Stem (.020" Dia. Tubing)

Stem Housing (.035" Dia. Tubing)

Plunger

Shutter Elements

Figure 3 MECHANICAL SHUTTER

flow duration, but shorter than the time required for the first reflected wave to pass the model, do not change the standoff dimension. From the exposure point of view, best results are obtained if the shutter is kept open somewhat longer than the entire flow duration to insure complete utilization of the available luminosity. In such a case, reflections from the end plate, located 16 inches from the model, give sufficient illumination to the model and the bow shock. As a result, even the bow shock itself becomes visible and a composite exposure of model, shock layer, and the bow shock extending around the model can be obtained. Contrast of the exposure can also be adjusted by changing the light reflection characteristics of the end plate.

Pictures were taken using a Polaroid camera and 3000 speed film. Data discussed in this report were obtained from two hemispherical cylinders 3/8 inch and 3/4 inch in diameter, respectively. Shock Mach number range was between 10.7 and 14.3 over a range of densities corresponding to initial pressures between 1.5 mm Hg and 0.05 mm Hg. Reduction of light intensity and flow duration time did not permit measurements at densities below 0.05 mm Hg. However, this range might be increased by increasing the shock Mach number and/or model diameter.

III. DISCUSSION

A. Stagnation Point Radiation

To date, the preponderance of experimental radiation data have been collected by observing regions behind incident and reflected shock waves in shock tube experiments. The application of these results to useful interpretation of in-flight conditions is hindered by the lack of duplication of temperature gradients that exist in flight. However, radiation calculations may be based on such information using simplifying assumptions concerning the nature of the shock layer.

For example, the shock layer may be considered a plane slab of infinite extent and thickness equal to the standoff distance Δ. If the temperature and density are uniform throughout (stagnation conditions are commonly assumed), then the radiation incident upon the stagnation region is given by

$$I_{T,p} \cong 2\pi\Delta \int_0^\infty \mu'_\nu B_\nu(T)\, d\nu \tag{1}$$

where μ'_ν = $\mu_\nu [1 - \exp(h_\nu / k T_s)]$

μ_ν = absorption coefficient at frequency ν

h = Planck's constant

$B_\nu(T)$ = specific intensity for a black body

Alternatively, the radiation on the stagnation region from a uniform region bounded by a hemispherical bow shock is

$$I_{T_s} = 2\pi\Delta k_s \int_0^\infty \mu'_\nu B_\nu(T)\, d\nu \tag{2}$$

where k_s is the radiation shape factor. Since $k_s < 1$, it is clear that the geometry of the surface will exert some influence on the radiation received at the stagnation point. However, if the radiation originates only in a thin region behind the bow shock, the radiation flux would be

$$I_{T_f} = 2\pi (R'/R)^2 \int_0^\infty \mu'_\nu B_\nu(T)\, d\nu \tag{3}$$

where $R' = R + \Delta$. It is clear that provided stagnation conditions are maintained, the ratio of intensities is only affected by the body radius and the standoff distance.

To test these simple analyses, it is convenient to investigate the radiant intensity at the stagnation region of a hemisphere-cylinder. For this case, Δ is approximately equal to $R(\rho_{\infty}/\rho_s)^{1/2}$, and Eq (1) for the infinite plane representation of the shock layer indicates that the intensity $I_{T,p}$ varies directly as the body radius. This is essentially true for Eq (2) as well; the distinction is only in the shape factor k_s.

On the other hand, if the radiation emanates only from a thin region behind the bow shock, the intensity will be essentially independent of radius. This may be demonstrated by rearranging Eq (3) and neglecting terms which are second order in Δ/R, that is:

$$I_{T_f} = 2\pi\,(1 + 2\Delta/R)\int_0^{\infty} I'_{\nu}\, d\nu \qquad (4)$$

or

$$I_{T_f} = 2\pi\,[1 + 2\,(\rho_{\infty}/\rho_s)^{1/2}]\int_0^{\infty} I'_{\nu}\, d\nu$$

where $I'_{\nu} = \mu_{\nu} B_{\nu}(T)$.

Thus, it appears possible to check the assumption of a uniform radiation field within the shock layer under conditions in which gas chemistry is in equilibrium behind the bow shock by observing the variation of radiation flux with body radius. Where the gas chemistry significantly departs from equilibrium conditions while the flow field remains inviscid, one would expect the radiation profile across the shock layer to be quite non-uniform.

We may infer this behavior from the results of Duff and others[3] who have shown that where non-equilibrium chemistry prevails, there is a region near the bow shock of excessive intensity associated with the "overshoot" phenomenon. Since the overshoot phenomenon is independent of body dimensions and dependent only upon the density ratio across the shock, one would expect the radiation intensity to scale directly as the density, as has been indicated in Eq (3).

As the density is further reduced and the flow field no longer is inviscid, it is clear that the relationship between radiation and flow field is not as clear. Radiation intensity will continue to decrease with decreasing density; simultaneously, the total volume of radiating gas will become smaller as the standoff distance becomes smaller with increasing viscous phenomena.

B. Standoff Distance

The measurement of the standoff distance provides a simple method of qualitatively estimating the degree of departure from equilibrium of the gas behind the bow shock. In addition, it yields a measure of the volume of gas available for radiation to the surface. It has already been shown[4,5] that standoff distance can be determined from mass transfer considerations alone, with the principal variable affecting its value being the density ratio ρ_∞/ρ_s across the shock. The velocity ratio is essentially unaffected by speed and dissociation. Experimental values of Δ/R are plotted in Figure 4 as functions of the density ratio calculated from Feldman's[6] tables for equilibrium air. The theories of Van Dyke, Serbin[4,5], and others are shown for comparison. It will be noted that at lower Mach numbers and $\rho_2/\rho_3 \cong \rho_\infty/\rho_s$ greater than 0.15, the data correlate well with the Van Dyke

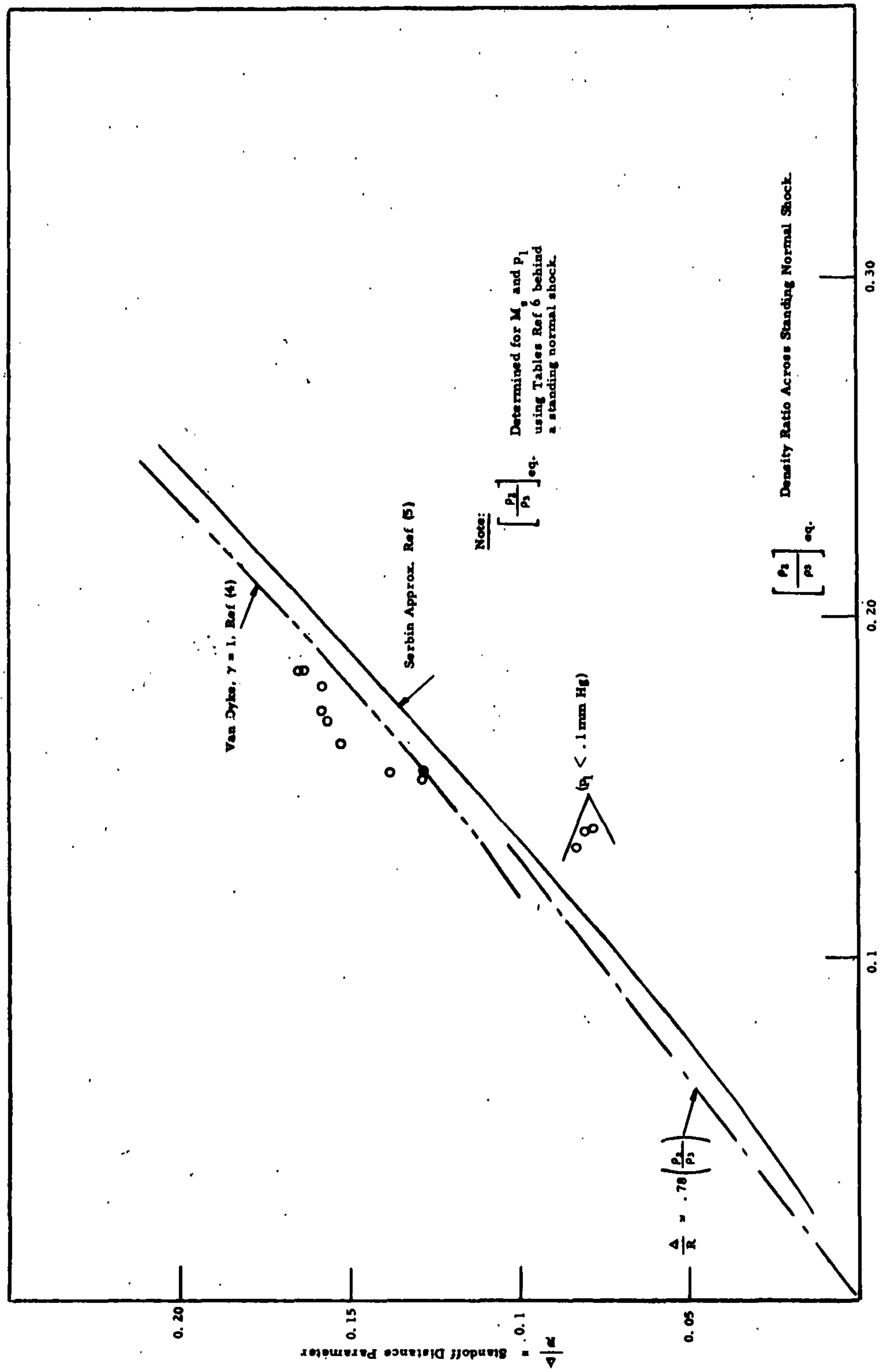


Figure 4 THEORETICAL AND EXPERIMENTAL RESULTS FOR STANDOFF DISTANCE PARAMETER

analysis. Below $\rho_2/\rho_3 = 0.15$, the disagreement is more pronounced, possibly because of errors produced by poorer optical resolution at low densities and non-equilibrium chemistry on either side of the bow shock.

By considering the effect of upstream conditions on flow variables across the shock, it is possible to estimate the directions of the error introduced by the assumption of an equilibrium state for the gas behind the incident normal shock, which produces the flow around the model. As the initial pressure is lowered, there is an accompanying decrease in available test time. This effect has been predicted by Roshko[7] and shown in a recent paper by Hacker and Wilson[8]. Coupled with the decrease in flow duration, chemical relaxation times in the gas become longer. For some of the experiments described here (0.05 mm $< p_1 < 0.1$ mm Hg), the characteristic relaxation time for molecular oxygen vibrational and dissociation equilibrium is almost equal to the total available test time ($\sim 10\,\mu$sec). It is evident that an accurate description of the gas composition and its flow properties is difficult to establish. Also, at higher densities ($p_1 > 0.1$ mm Hg), where equilibrium assumptions are valid, the flow about the body is still uncertain since the free stream has been heated and dissociated ahead of the bow shock. Inger[2] has described a model for the stagnation region in the presence of a partially dissociated free stream. Significant increases in shock detachment distance are predicted for increasing levels of dissociation. The free stream dissociation level also increases the stagnation density ratio.

These facts suggest the probable reasons for the deviations of the present data from the theoretical values. First, at the higher values of density ρ_2/ρ_3, the measured values of Δ/R are higher than predicted by theory. However, because of air dissociation ahead of the bow shock, the density ratio under experimental conditions must actually have been larger than the values for undissociated air obtained from reference 6. Correction of the density ratio to include pre-dissociation effects would therefore shift the experimental data closer to the Van Dyke solution.

At the lower density ratios, the experimental Δ/R ratios are considerably below the values predicted by theory. If we can accept the fact that an inviscid field exists in the portion of the experimental range examined, and if the optical error is assumed constant throughout, then the deviation at the low density regime may be identified as resulting from possible non-equilibrium gas effects. It is indeed in this regime that the relaxation times become quite long and appreciable non-equilibrium effects occur behind both incident and bow shocks.

It has been shown by Burke and Boyer[9] that the non-equilibrium effects accompanying the expansion of air in the shock tunnel markedly affect the conditions within the shock layer. Their analysis is applicable as well to the conditions met in the shock tube. Under conditions where non-equilibrium chemical processes are important in the shock layer field, simulation of actual flight conditions is out of the question. However, at such conditions where the level of pre-dissociation in the external flow is small, as obtained with relatively weak incident shock waves, it is possible to achieve at least partial simulation in the shock layer at the stagnation stream line. This has been shown in recent experiments[8] where shock Mach numbers of less than 14 were used to achieve stagnation heat transfer data at Reynolds numbers as low as 500. If a similar experiment is carried out at low Re and $M_s < 15$, the observed radiation phenomena at these relatively low densities may be difficult to interpret. For example, at $M_s \sim 14$ and $p_1 = 0.05$ mm behind a normal shock in air the oxygen is completely dissociated at equilibrium with an atom concentration of 34 per cent. Non-equilibrium effects would of course reduce this value. The effect of such a concentration of atoms would make any evaluation of the shock layer radiation extremely sensitive to actual conditions in the flow field.

IV. SUMMARY

Standoff distance measurements compared with theories derived from equilibrium considerations show the following:

1. Reasonable agreement at densities corresponding to initial pressures above 0.5 mm Hg at $T_s \sim 6000°K$, suggesting chemical and thermodynamic equilibrium at these flow conditions,
2. Deviations at pressures $p_1 \leq 0.1$ mm Hg which indicate possible lack of attainment of chemical equilibrium.

Preliminary total radiation intensity measurements at $p_1 = 0.5$ mm and 1.5 mm initial pressure and $T_s = 6300°R$ indicate that the intensity ratio varies directly with the model scale or standoff distance ratio, or

$$I_1/I_2 \cong R_1/R_2 \cong \Delta_1/\Delta_2$$

This means that the radiating zone behind the bow shock at these flow conditions is essentially uniform. No definite conclusions have been made about the degree of equilibrium.

V. FUTURE WORK

The next phase of this investigation will concern further radiation measurements at the stagnation point of hemispherical cylinders. Two, or if necessary, three model sizes will be used. The steps will be as follows:

1. Total intensity measurements at 0.5 and 1.5 mm Hg initial pressure to supplement the existing data.

2. Total intensity measurements at pressures below 0.5 mm Hg (0.1 mm and 0.05 mm). In this flow regime, intensity may no longer be proportional to the model scale factor. Thus, this experiment will indicate possible lowest limits of p_1 for a particular T_s, below which the use of the shock tube for re-entry simulation in radiation studies becomes questionable.

3. Spectral distribution of radiation at flow regimes where total intensity ratio scales as the model size. If the zone of uniform total radiation is in an equilibrium state and relaxation effects are unimportant, then the intensity ratio should be proportional to the scale factor at any wavelength. Appearance of excessive radiation from particular species will enable us to draw conclusions about the extent of chemical non-equilibrium in this flow regime.

4. Similar spectral measurements in the low density regime where non-equilibrium conditions are expected. These may yield information pertaining to non-equilibrium radiators and their contribution to the radiant stagnation point heat transfer in shock tube flows.

5. Correlation of radiation intensity measurements behind the bow shock with measurements made behind a normal shock. Such comparison of data obtained in low density flows may yield an estimate of a degree to which this regime may be used for re-entry simulation.

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